25 years of learning collective flow with Art

Jean-Yves Ollitrault

Symposium on collective flow in nuclear matter:
a celebration of Art Poskanzer's life and career,
LBNL, Dec.9-10, 2022

Art Poskanzer was one of the most important colleagues in my career. His constant support, from day #1, was essential.

I still have 763 emails from Art, after he taught me not to delete professional emails. We co-authored a few papers together but we had many interactions beyond these papers.

This presentation is a very incomplete history of collective flow, as seen through the window of my interactions with Art.

1. Early days

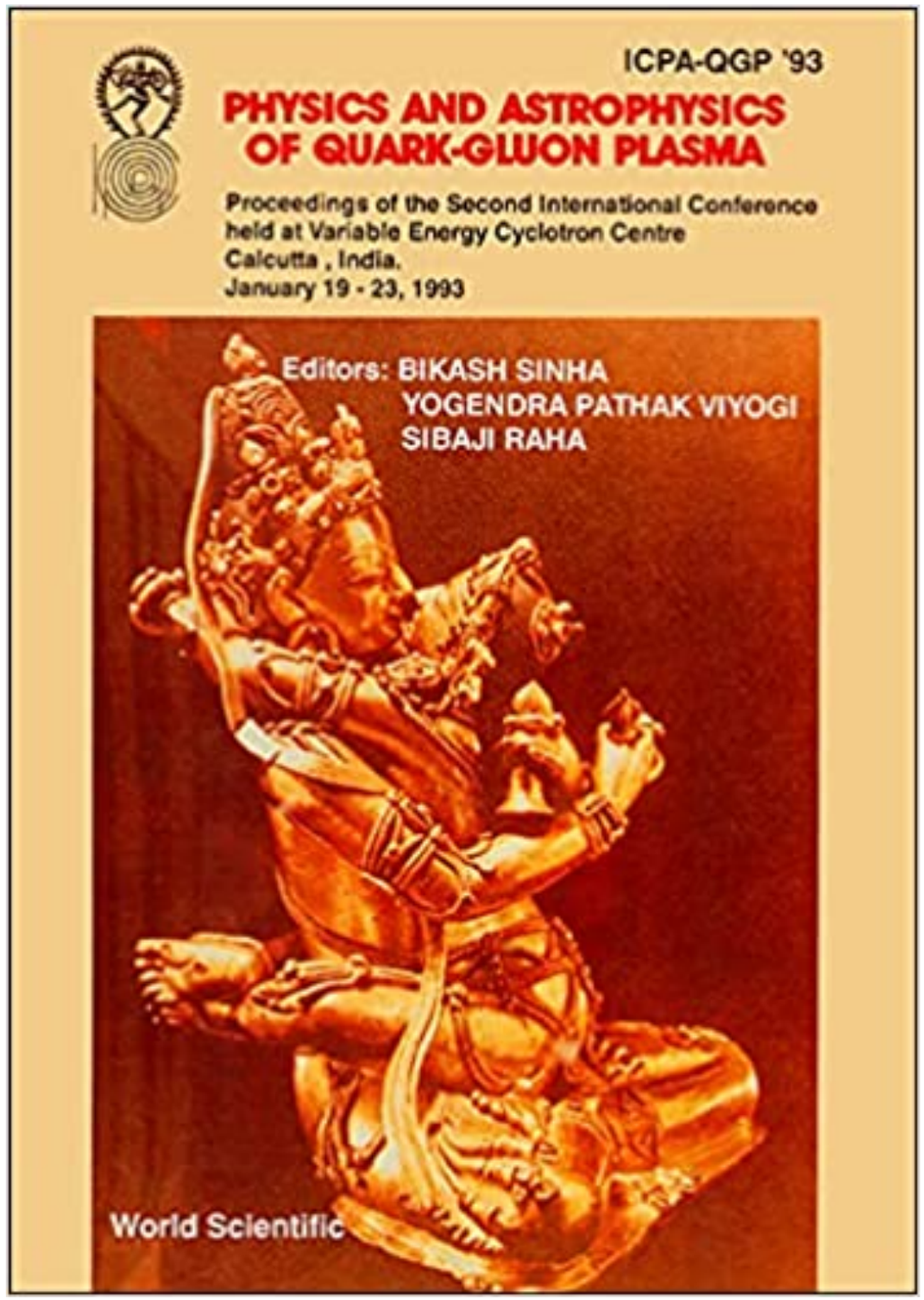
2. Searching for collectivity

3. Understanding fluctuations

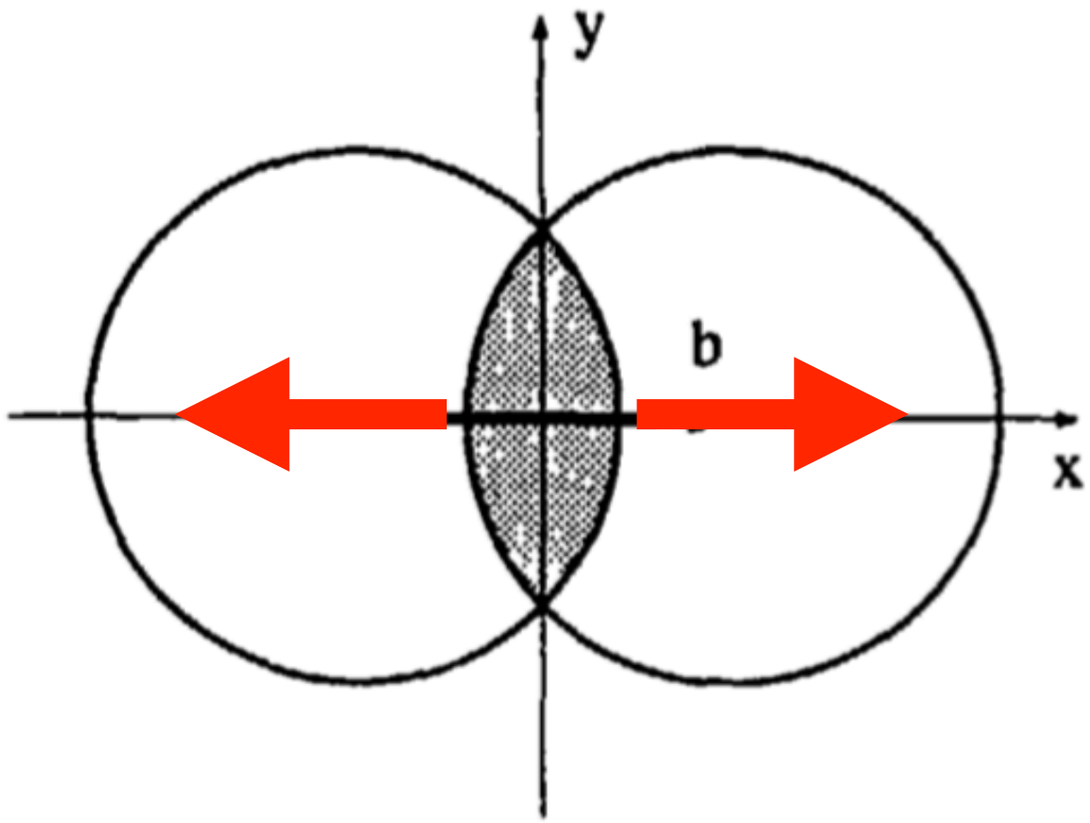
January 1993

Calcutta

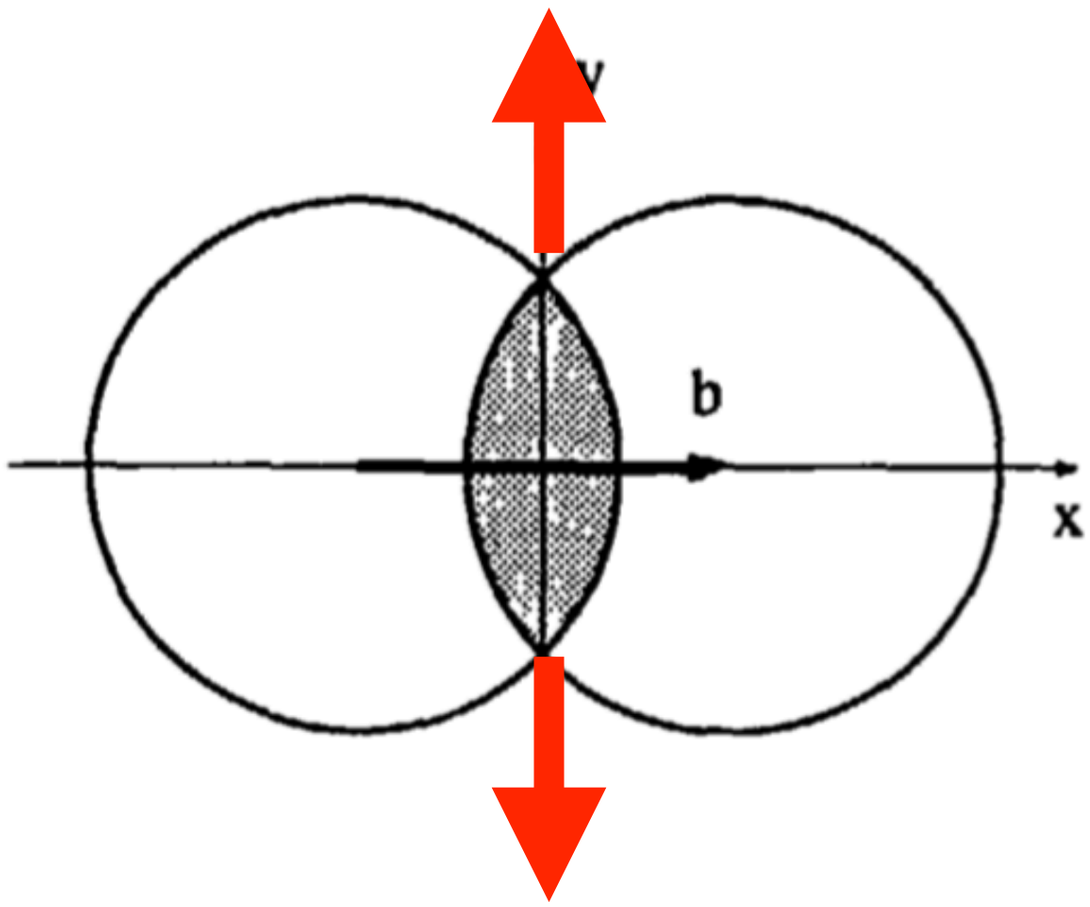
in plane or out of plane?



I presented my recent prediction that at ultrarelativistic energies, there would be more momentum emitted parallel to the reaction plane x:



Art told me after my talk:
We measured this at the Bevalac, and we observe the opposite: particles are « squeezed out » of the reaction plane.



I realized that the physics changes as a function of collision energy.

We predict a larger flow *in* the reaction plane than *out of* the reaction plane; this seems in contradiction with the squeeze–out effect observed at Bevalac. However, the situation is quite different: the origin of squeeze–out is believed to be that both target and projectile nuclei obstruct the way and the matter compressed in the overlap zone can only escape out of the reaction plane. But at ultrarclativistic energies, the time it takes for the nuclei to cross each other (of the order of 1 fm/c) is much smaller than the typical time it takes for transverse flow to develop, which is of the order of the nuclear size (about 10 fm/c). Thus the matter created in the central rapidity region does not "see" the target and projectile nuclei any more. Note further that the main contribution is expected to come from mesons, instead of nucleons at intermediate energies. Let us put it in another way: the squeeze–out effect results from an interaction between the participants which try to escape the fireball and the spectators which bar the way out, while anisotropy results from the interaction of particles in the central rapidity region among themselves. Note that the squeeze–out effect is observed to decrease with increasing incident energy[10].

Acknowledgements

I wish to thank Profs. H. H. Gutbrod and A. M. Poskanzer for mentioning the works on squeeze–out of nuclear matter. I also thank J. P. Blaizot for reading the manuscript.

EXPERIMENTAL SUMMARY

ARTHUR M. POSKANZER
Lawrence Berkeley Laboratory
University of California, Berkeley, CA 94720, USA

ABSTRACT

An overview of the experimental talks presented at this conference is given.

The Bevalac, which is now shutting down, was the accelerator which started the whole field of relativistic heavy ion physics. However, the Bevalac needed very heavy beams before new physics started to come out. Ollitrault, in his talk, pointed out that really heavy nuclei were needed for the observation of collective flow. In the higher energy regime that we are now considering there has been so far only one week of really heavy beams—gold at the AGS. Therefore, this field is just getting started. The qualitative differences of these first Au data from the lighter ion data were very impressive at this conference.

The opportunities which are opening up in this field are enormous. There are the gold beams at the AGS that started in 1992 and will continue. Lead beams at the SPS will start in October 1994. RHIC will have gold beams in late 1997. And finally, the LHC should have lead beams by the turn of the century. The exciting prospects for experiments at both RHIC and the LHC were shown by Seto for PHENIX, Harris for STAR, Gutbrod for ALICE, and Contardo for the CMS. In addition, Llewellyn-Smith gave a very comprehensive description of the entire CERN program.

January 1995

Monterey

Art was busy chairing QM'95 and I didn't seem him much, but I was inspired by some of the talks

Preface

The Quark Matter '95 Conference was held 9–13 January 1995 at the Monterey Conference Center in Monterey, California, where the beautiful Steinbeck Auditorium provided a perfect setting for the plenary sessions. Memorable events included the buffet dinner at the fascinating Monterey Bay Aquarium, the welcome reception, and the excursion to Pt. Lobos State Park. The rain actually abated long enough for the excursion to take place.

The conference was attended by 458 participants from 33 countries. Fifty percent of the participants were from outside the US. In addition, there were 41 companions. With staff, speakers for the companions, and exhibitors there were a total of about 515 people present at the Conference.

. . . .

A very interesting companions program was organized by Lucille Poskanzer. It ranged from understanding what is quark matter to understanding the people who search for it. She wishes to thank the speakers on her program — Jay Marx (LBL), Audry Lynch, Alan Leveton, and Milos Radakovich.

. . . .

On the next page is a graph showing the increase in attendance at Quark Matter conferences over the years. The best fit to the slope of the corresponding semi-log graph is 10%/year of 14%/conference. This graph indicates the strong growth in this field of physics. With RHIC and LHC yet to come we can expect this growth to continue and to have many great conferences in the future.

Art Poskanzer, Chairman

Observation of Collective Effects in Λ Production at 2 GeV/nucleon

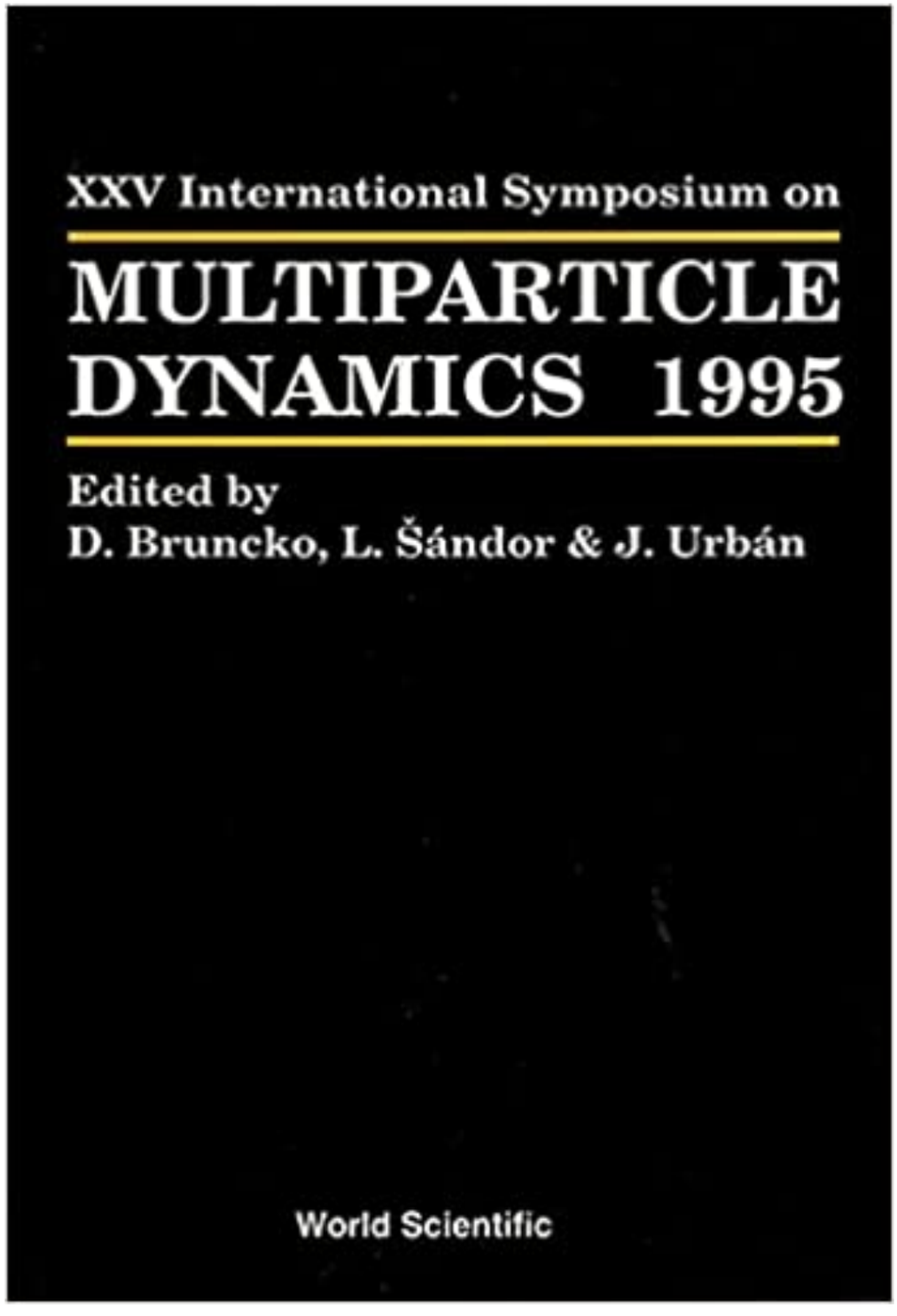
M. Justice

Kent State University
Kent, Ohio 44242

EOS Collaboration

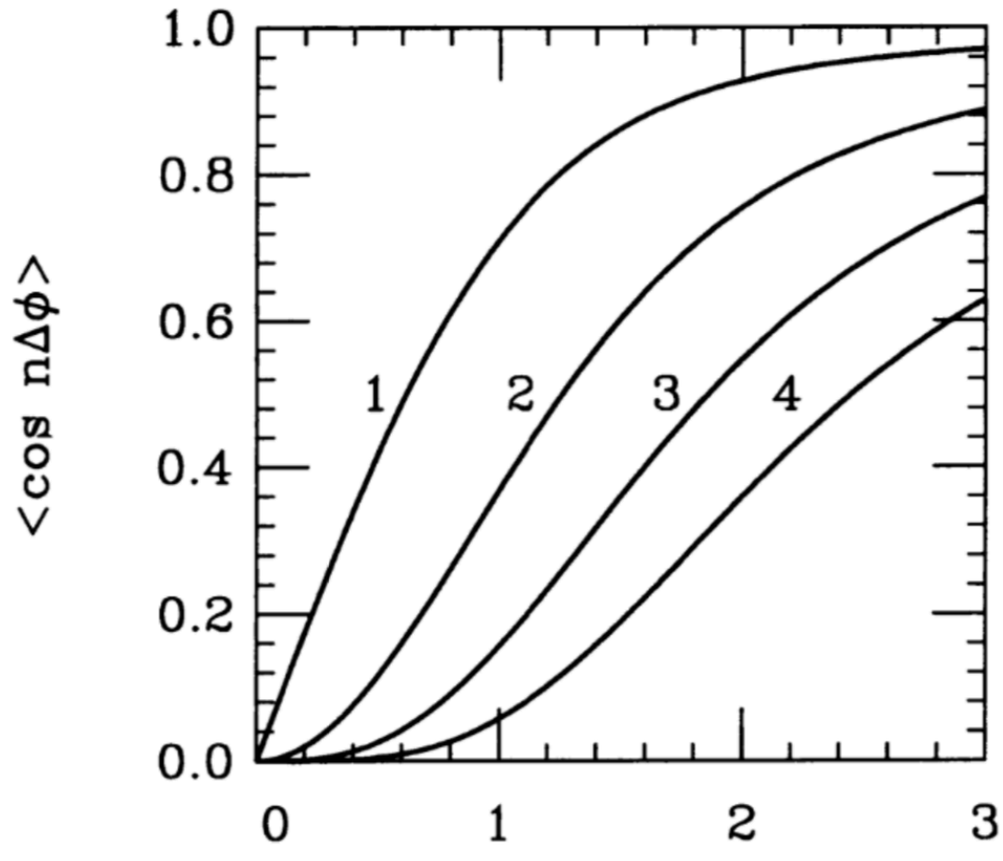
In one of the parallel talks, a postdoc from Kent state presented uncorrected azimuthal distributions of Λ baryons relative to the event plane.

Right after the conference, I worked out a systematic reconstruction method, by correcting each Fourier coefficient for the event plane resolution



A METHOD OF RECONSTRUCTING AZIMUTHAL DISTRIBUTIONS IN HEAVY ION COLLISIONS

Jean-Yves OLLITRAULT *
Service de physique théorique,† C. E. Saclay
91191 Gif-sur-Yvette, France
E-mail: ollitrault@cea.fr



$$\langle \cos n\Delta\phi \rangle = \frac{\sqrt{\pi}}{2} \bar{\chi} e^{-\bar{\chi}^2/2} \left[I_{\frac{n-1}{2}} \left(\frac{\bar{\chi}^2}{2} \right) + I_{\frac{n+1}{2}} \left(\frac{\bar{\chi}^2}{2} \right) \right]$$

The first curve, and the concept of event-plane resolution, had actually been introduced earlier on by Sergei Voloshin in his seminal 1994 paper with Zhang.
This formed the basis of the event-plane method, recently selected as one of the milestone papers of PRC

Milestone

Methods for analyzing anisotropic flow in relativistic nuclear collisions

A. M. Poskanzer and S. A. Voloshin
Phys. Rev. C **58**, 1671 – Published 1 September 1998

An article within the collection: *Physical Review C* 50th Anniversary Milestones

December 1997

Tsukuba

establishing terminology

ELSEVIER

Nuclear Physics A638 (1998) 463c–466c

NUCLEAR PHYSICS A

Directed and Elliptic Flow in 158 GeV/Nucleon Pb + Pb Collisions

A.M. Poskanzer[a] for the NA49 Collaboration

[a]Lawrence Berkeley National Laboratory Berkeley, CA 94720

Art presented the first flow analysis of the NA49 collaboration

I was giving the plenary talk on flow. Art approached me before my talk and told me that it was a good opportunity for establishing the terminology on this topic

Flow systematics from SIS to SPS energies

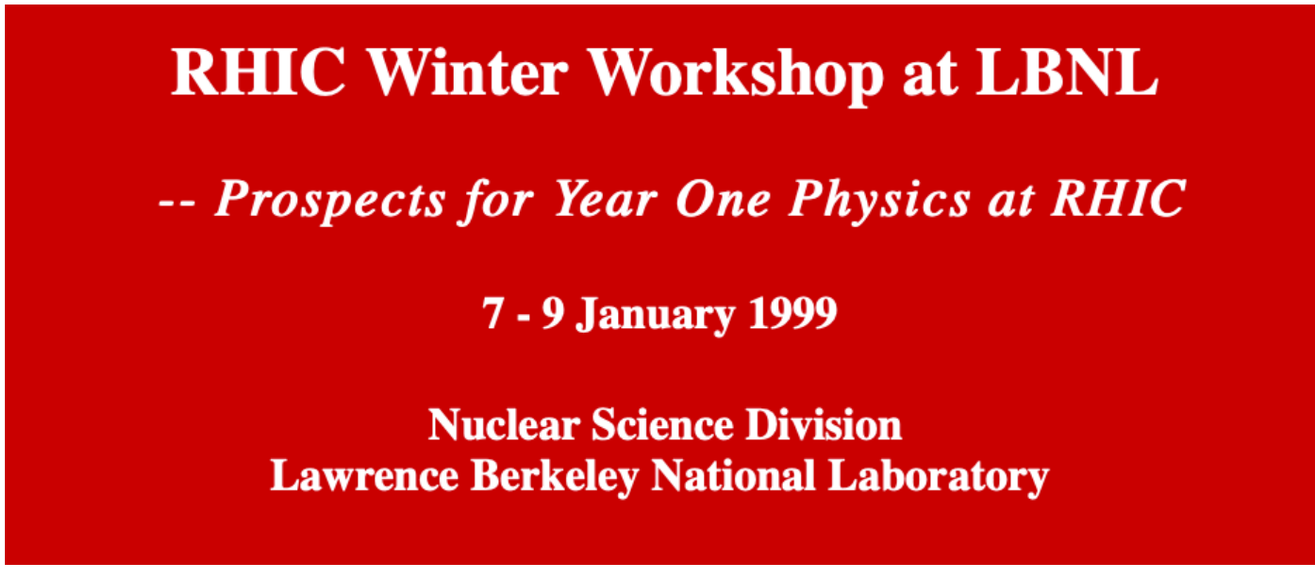
Jean-Yves Ollitrault[a] *

[a]Service de physique théorique, C.E. Saclay,F-91191 Gif-sur-Yvette cedex

The various flow phenomena observed at energies between 50 AMeV and 160 AGeV are reviewed. I first define three types of flow: directed flow and elliptic flow, which are the two first Fourier components of the azimuthal distribution in non-central collisions; radial flow, which is deduced from an analysis of transverse momentum spectra in central collisions. Then, I review the observations of directed flow and elliptic flow, with emphasis on recent results. I discuss their dependence on various parameters: global geometry (impact parameter, mass numbers of colliding nuclei and bombarding energy) and individual observables (rapidity, transverse momentum and particle type). Finally, I explain how azimuthal distributions can be measured experimentally.

January 1999

Berkeley



transport or

hydro?

Session Chair: Art Poskanzer

Speaker	*Title*	*Time*
Jean-Yves Ollitrault	Flow	14:00-14:35

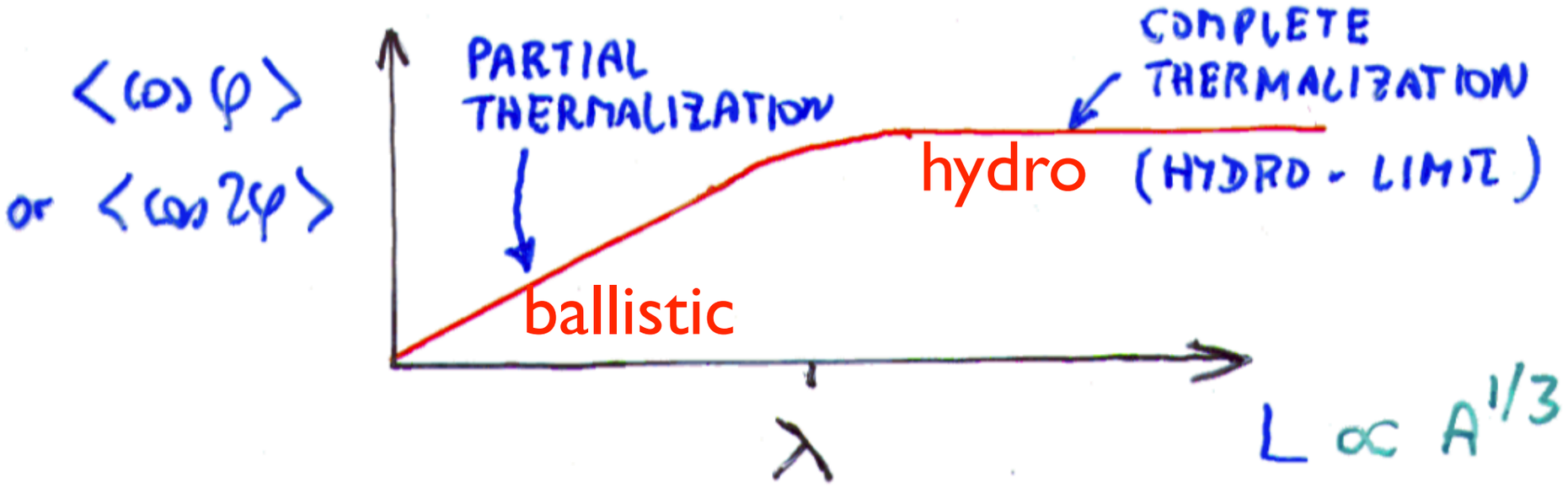
- LOCAL THERMAL EQUILIBRIUM (HYDRO - LIMIT) IS ACHIEVED IF

$$\lambda \ll L$$

λ: MEAN FREE PATH ($= \frac{1}{\sigma n}$)

L: SIZE OF THE SYSTEM ($\propto A^{1/3}$)

- FLOW OBSERVABLES DEPEND ON L TYPICALLY LIKE (AT FIXED ENERGY)

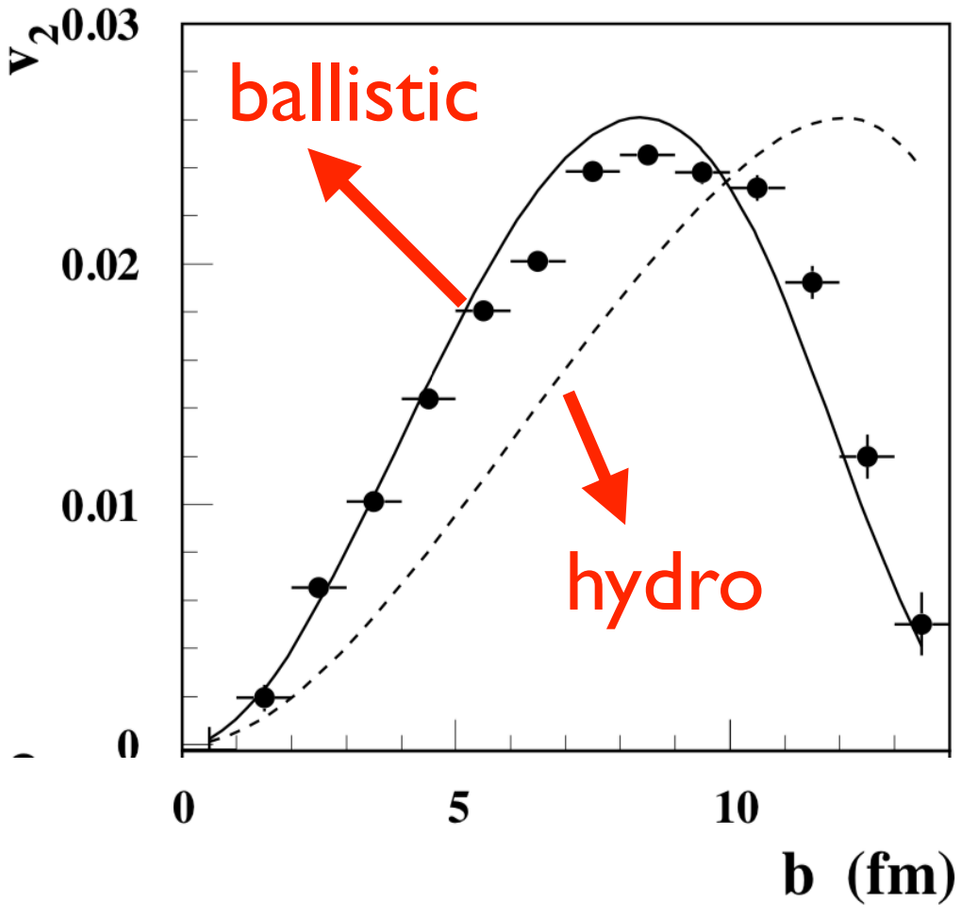


Sergei and Art applied this idea

The Physics of the centrality dependence of elliptic flow #1

S.A. Voloshin (LBL, Berkeley), Arthur M. Poskanzer (LBL, Berkeley) (Jun, 1999)

Published in: *Phys.Lett.B* 474 (2000) 27-32 • e-Print: nucl-th/9906075 [nucl-th]



They showed that tranport calculations using RQMD were in the ballistic regime

This was forgotten soon after the first RHIC results, which established that Au-Au collisions are *large systems*, where hydro applies.

Recently re-discovered in the context of *small systems*

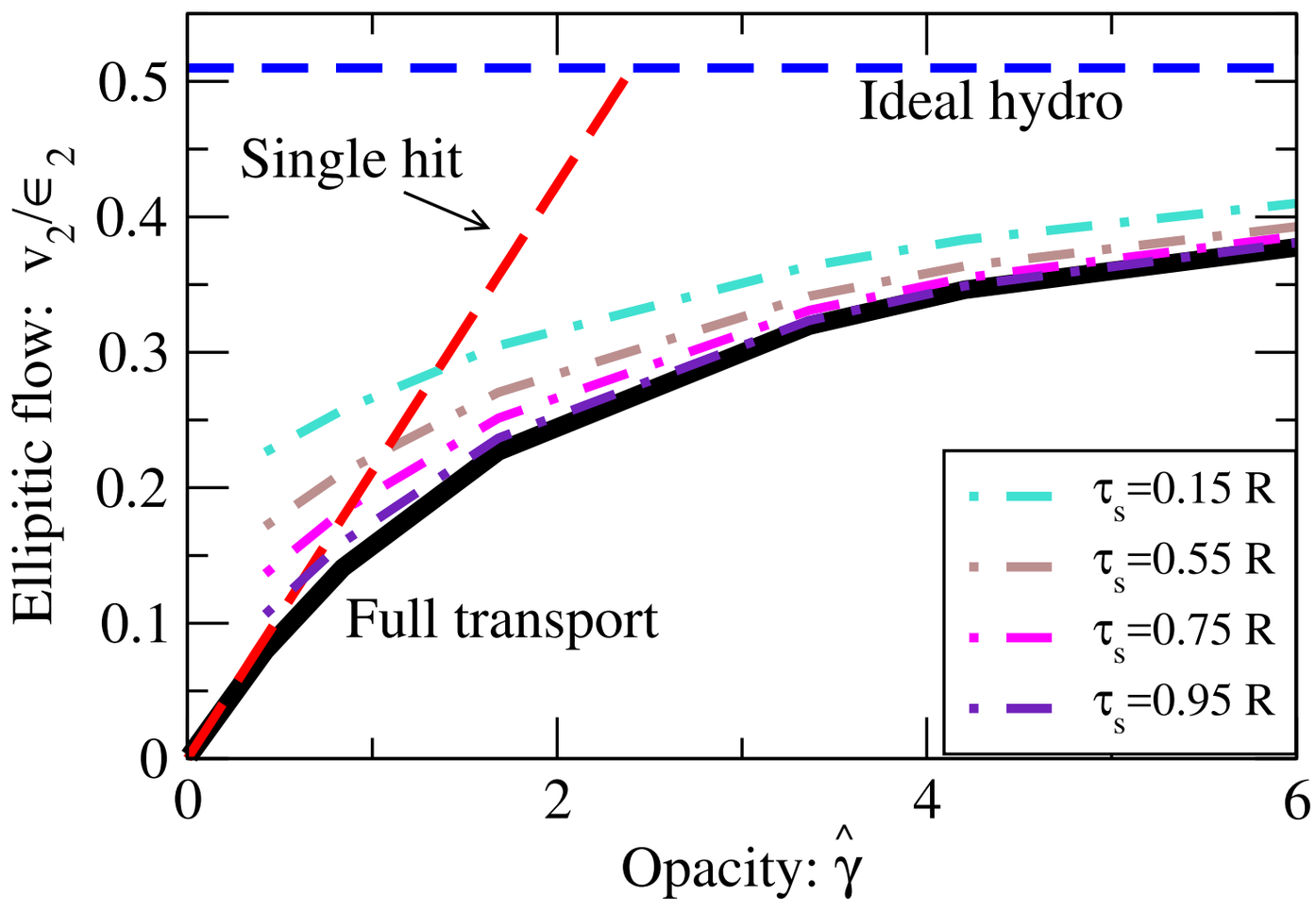
Opacity dependence of elliptic flow in kinetic theory #1

Aleksi Kurkela (CERN and Stavanger U.), Urs Achim Wiedemann (CERN), Bin Wu (CERN) (May 10, 2018)

Published in: *Eur.Phys.J.C* 79 (2019) 9, 759 • e-Print: 1805.04081 [hep-ph]

pdf DOI cite claim reference search 54 citations

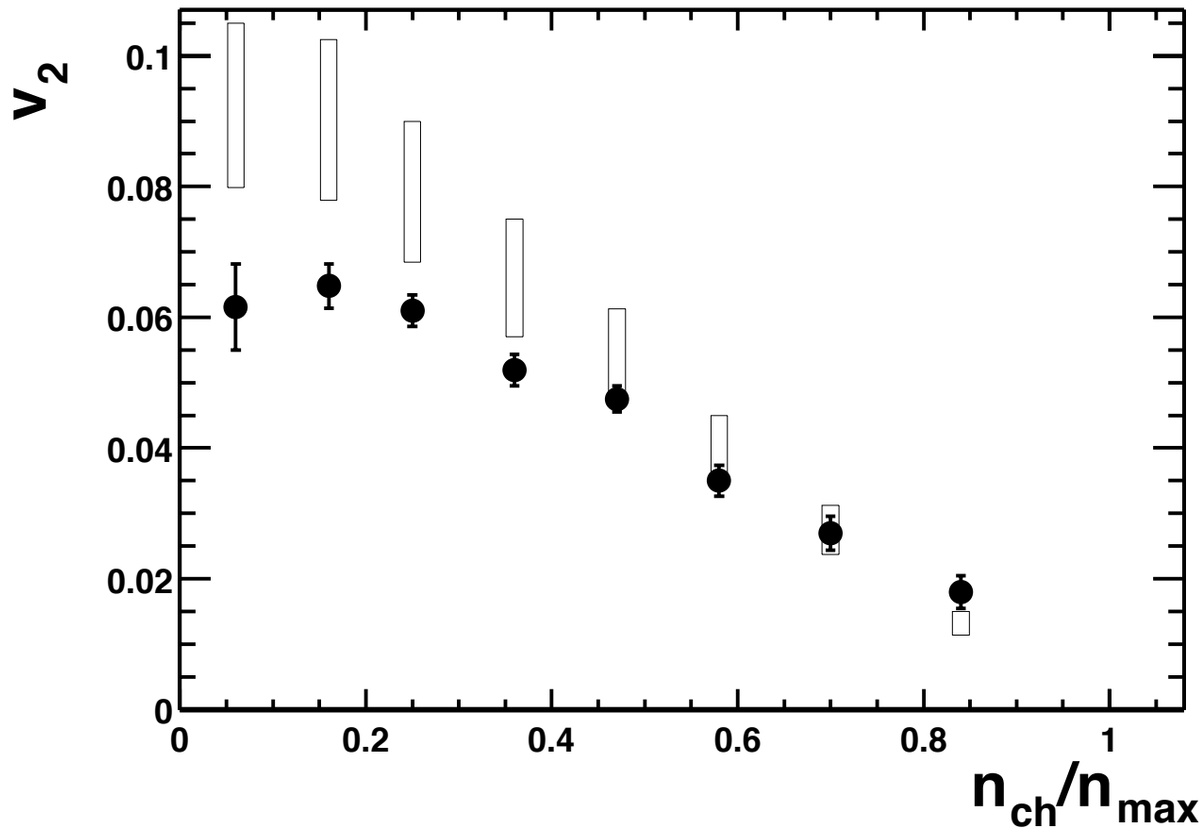
Kinetic theory pre-hydrodynamic stage:



September 2000

Berkeley

the RHIC breakthrough



Elliptic flow in Au + Au collisions at (S(NN))(1/2) = 130 GeV** #1

STAR Collaboration • K.H. Ackermann (Munich, Max Planck Inst.) et al. (Sep, 2000)

Published in: *Phys.Rev.Lett.* 86 (2001) 402-407 • e-Print: nucl-ex/0009011 [nucl-ex]

pdf DOI cite datasets claim reference search 807 citations

1. Early days

2. Searching for collectivity

3. Understanding fluctuations

Nonflow

- In 1999 and 2000, in a series of papers with Mai Dinh and Nicolas Borghini, we argued that most existing analyses of flow at AGS and SPS were biased by correlations such as Bose-Einstein quantum correlations, or global momentum conservation, which have nothing to do with flow.

- In particular, it implied that the v_1 and v_2 results published by NA49 in 1998 had a lot of nonflow bias.

- Art was enthusiastic and supportive from day #1. Not everyone was! Together with Sergei, the 5 of us wrote a paper on how to correct the event-plane method for momentum conservation. More importantly, we collaborated on the re-analysis of NA49 data, with the Frankfurt group. Art was (informally) the project leader.

Cumulants

- We thought that the only way of systematically getting rid of nonflow was to go beyond two-particle correlations and measure cumulants of higher-order correlations. We worked out the analysis method in 2000 and 2001 with Dinh and Borghini.

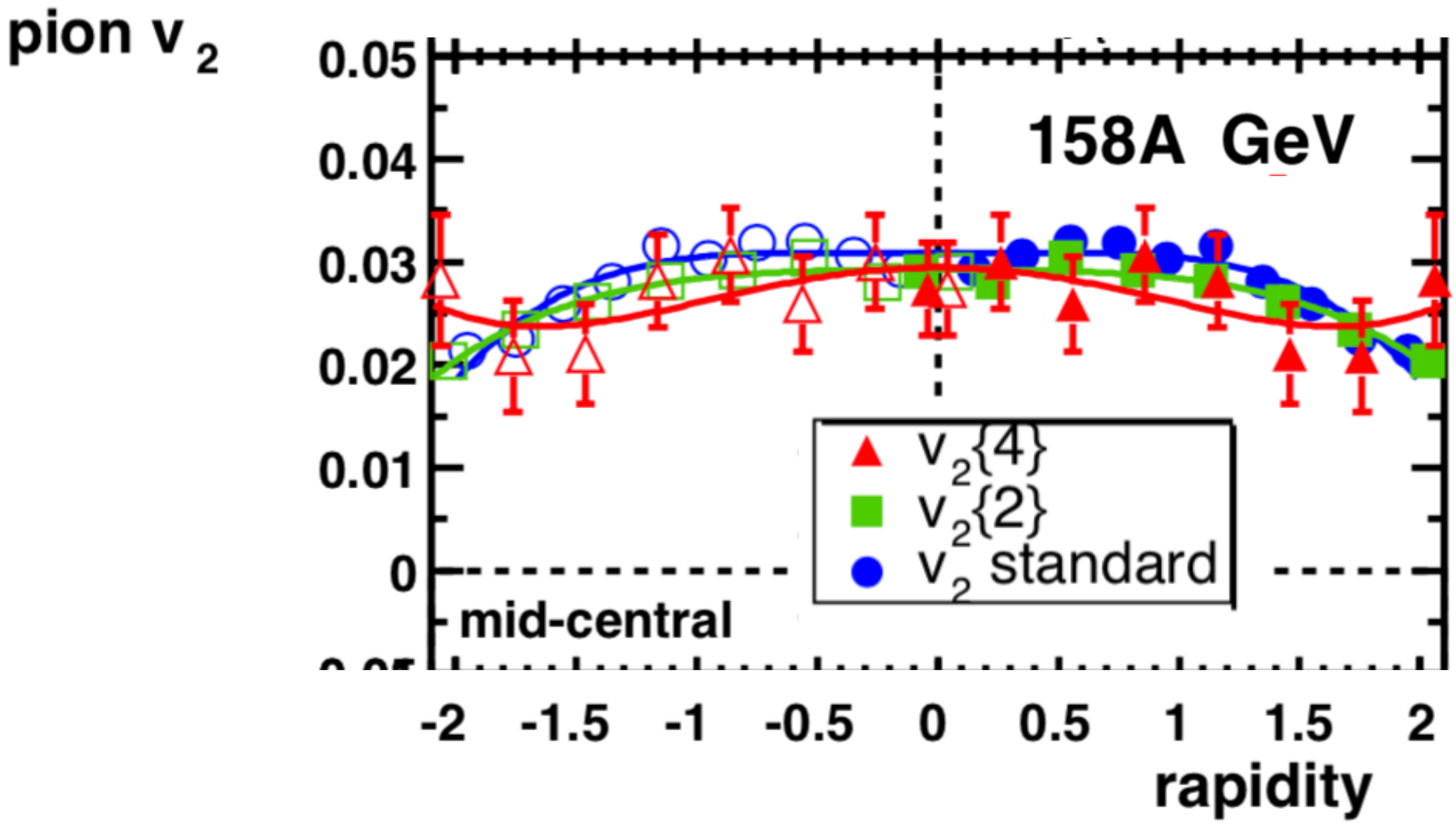
- It was first applied by STAR in 2002, by Aihong Tang (talk today).

- Mai Dinh applied the cumulant method to NA49 data a few months later. She was awarded the PhD prize of the French Physical Society (only one prize for all of physics) for her work.

Directed and elliptic flow of charged pions and protons in Pb + Pb collisions at 40-A-GeV and 158-A-GeV #1

NA49 Collaboration • C. Alt et al. (Mar, 2003)

Published in: *Phys.Rev.C* 68 (2003) 034903 • e-Print: nucl-ex/0303001 [nucl-ex]



Directed flow at RHIC

Borghini had the brilliant idea of analyzing the first harmonic, directed flow, by using elliptic flow as a reference. As soon as the paper was out, Art called me and said « This is how we will do it at STAR ».

Azimuthal anisotropy at RHIC: The First and fourth harmonics #1

STAR Collaboration • J. Adams (Birmingham U.) et al. (Oct, 2003)

Published in: *Phys.Rev.Lett.* 127 (2021) 6, 069901 (erratum), *Phys.Rev.Lett.* 92 (2004) 062301 • e-Print: nucl-ex/0310029 [nucl-ex]

pdf DOI cite datasets claim reference search 271 citations

A by-product of this analysis is that it gave the sign of elliptic flow, which one does not measure by analyzing elliptic flow alone:
First and only direct evidence that elliptic flow at RHIC is in plane!

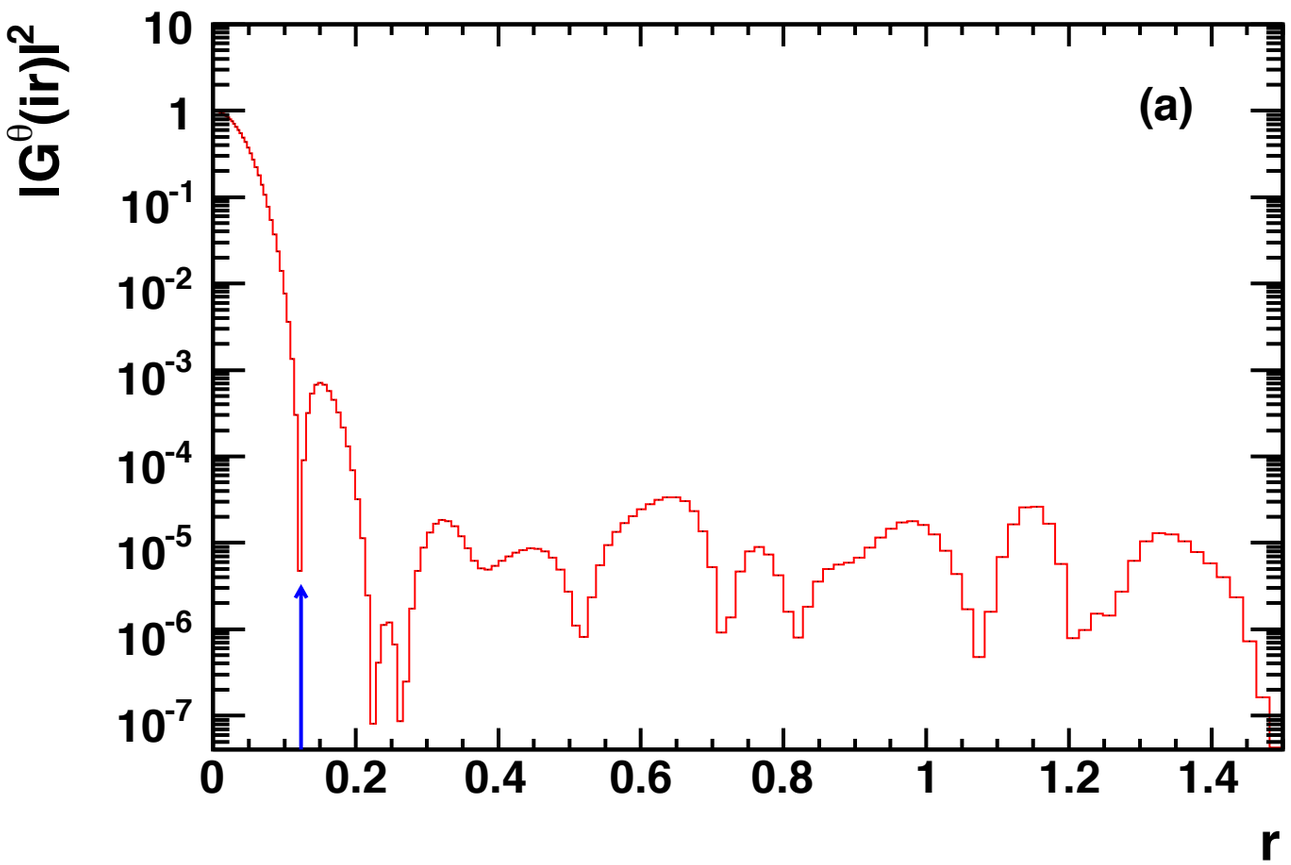
Lee-Yang zeroes

- In 2003, with Bhalerao and Borghini, I proposed yet another method to analyze elliptic flow. Eventually, I had found how to measure collectivity.
- Lee and Yang introduced this method to locate the liquid-gas phase transition in calculations. In the same way as the liquid-gas transition corresponds to the system becoming inhomogeneous (spontaneous symmetry breaking of translational invariance), elliptic flow corresponds to the breaking of rotational (azimuthal) symmetry: all directions are no longer equivalent.
- The method is very robust, and much simpler to implement than cumulants. Yet the added value is incremental, as results are practically identical. Not considered breakthrough research.
- *Only Art showed interest*. He coded the analysis himself. We discussed it when he visited Paris in 2006

Centrality dependence of charged hadron and strange hadron elliptic flow from s(NN)(1/2) = 200-GeV Au + Au collisions** #1

STAR Collaboration • B.I. Abelev (Illinois U., Chicago) et al. (Jan, 2008)

Published in: *Phys.Rev.C* 77 (2008) 054901 • e-Print: 0801.3466 [nucl-ex]



Fourier transform of the distribution of the flow vector. The first minimum, which is compatible with 0 within errors, is where collectivity lies.

1. Early days

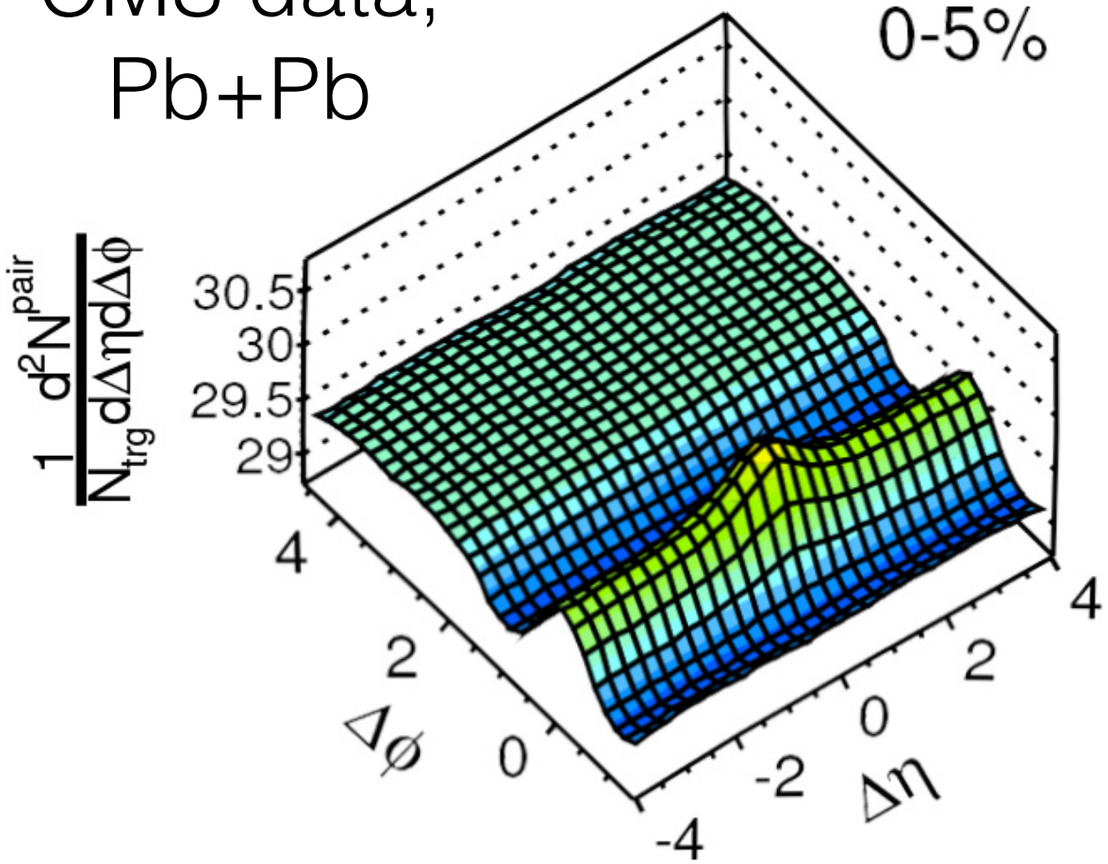
2. Searching for collectivity

3. Understanding fluctuations

Hydro need not be collective

- A gradual change of paradigm in the field. Already in 2003, PHENIX had shown that a rapidity gap suppresses nonflow: Pair correlations good enough, cumulants not needed.

CMS data, Pb+Pb



- More importantly, the beautiful wave (ridge) structure seen in pair correlations has a natural interpretation in terms of density fluctuations, stretched along the beam direction by the ultrarelativistic dynamics, and expanding according to hydro (Alver and Roland, 2010).

Art's contributions to fluct.

Elliptic flow in the Gaussian model of eccentricity fluctuations #1

Sergei A. Voloshin (Wayne State U.), Arthur M. Poskanzer (LBL, Berkeley), Aihong Tang (Brookhaven), Gang Wang (UCLA) (Aug, 2007)

Published in: *Phys.Lett.B* 659 (2008) 537-541 • e-Print: 0708.0800 [nucl-th]

pdf DOI cite claim reference search 199 citations

A breakthrough paper: Flow fluctuations as a small, Gaussian perturbation on top of in-plane elliptic flow.
Comes with a simple prediction: $v_2\{2\} > v_2\{4\} = v_2\{6\} = v_2\{8\}$

Effect of flow fluctuations and nonflow on elliptic flow methods #3

Jean-Yves Ollitrault (Saclay, SPhT), Arthur M. Poskanzer (LBL, Berkeley), Sergei A. Voloshin (Wayne State U.) (Apr, 2009)

Published in: *Phys.Rev.C* 80 (2009) 014904 • e-Print: 0904.2315 [nucl-ex]

pdf DOI cite claim reference search 189 citations

Non-Gaussian fluctuations

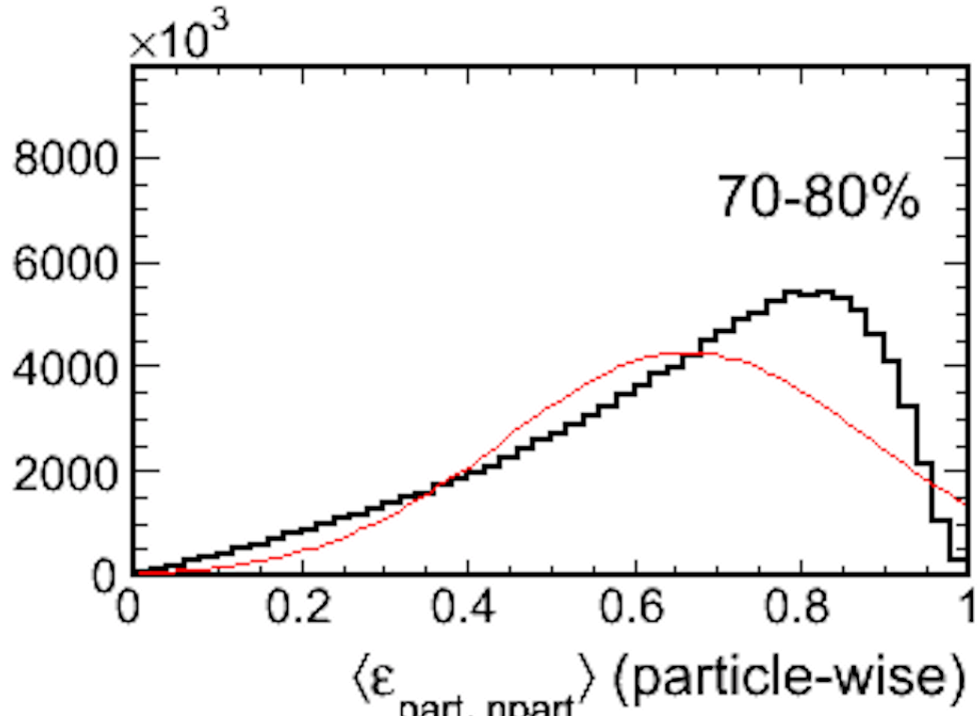
Sergei and Jean-Yves:

I am disturbed that for peripheral collisions the curves do not look Bessel-Gaussian-- they have a tail to low values, not high values. Is that possible?

Art

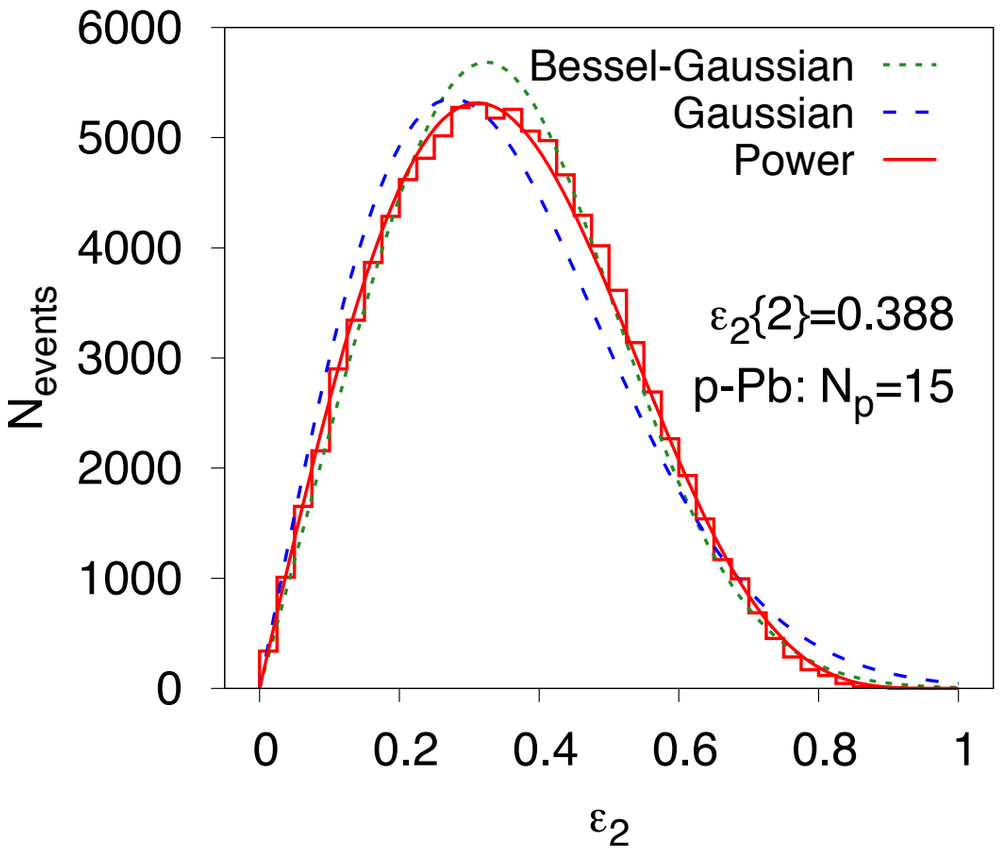
On Sep 3, 2009, at 2:03 PM, Art Poskanzer wrote:

> This figure is from Hiroshi Masui:



Art also pointed out that this discrepancy was due to the fact that ε was bounded by 1. I told him I'd think about it. It took > 4 years.

Elliptic flow in p+Pb collisions



We also found that the distribution of eccentricity was not quite Gaussian in simulations of p+Pb collisions.
We obtained a perfect fit by replacing the Gaussian with a Power law:

$$\exp(-\varepsilon^2/\sigma^2) \rightarrow (1-\varepsilon^2)^{\alpha}$$

which vanishes at $\varepsilon=1$.

Universal Fluctuation-Driven Eccentricities in Proton-Proton, Proton-Nucleus, and Nucleus-Nucleus Collisions

Li Yan and Jean-Yves Ollitrault
Phys. Rev. Lett. **112**, 082301 – F

JYO thanks Art Poskanzer for pointing out, back in 2009, that Bessel-Gaussian fits to Monte-Carlo Glauber calculations fail because they miss the constraint $\varepsilon_2 < 1$,

The Power distribution comes with a quantitative, parameter-free prediction for the hierarchy of successive cumulants
$v_2\{2\} > v_2\{4\} > v_2\{6\} > v_2\{8\}$

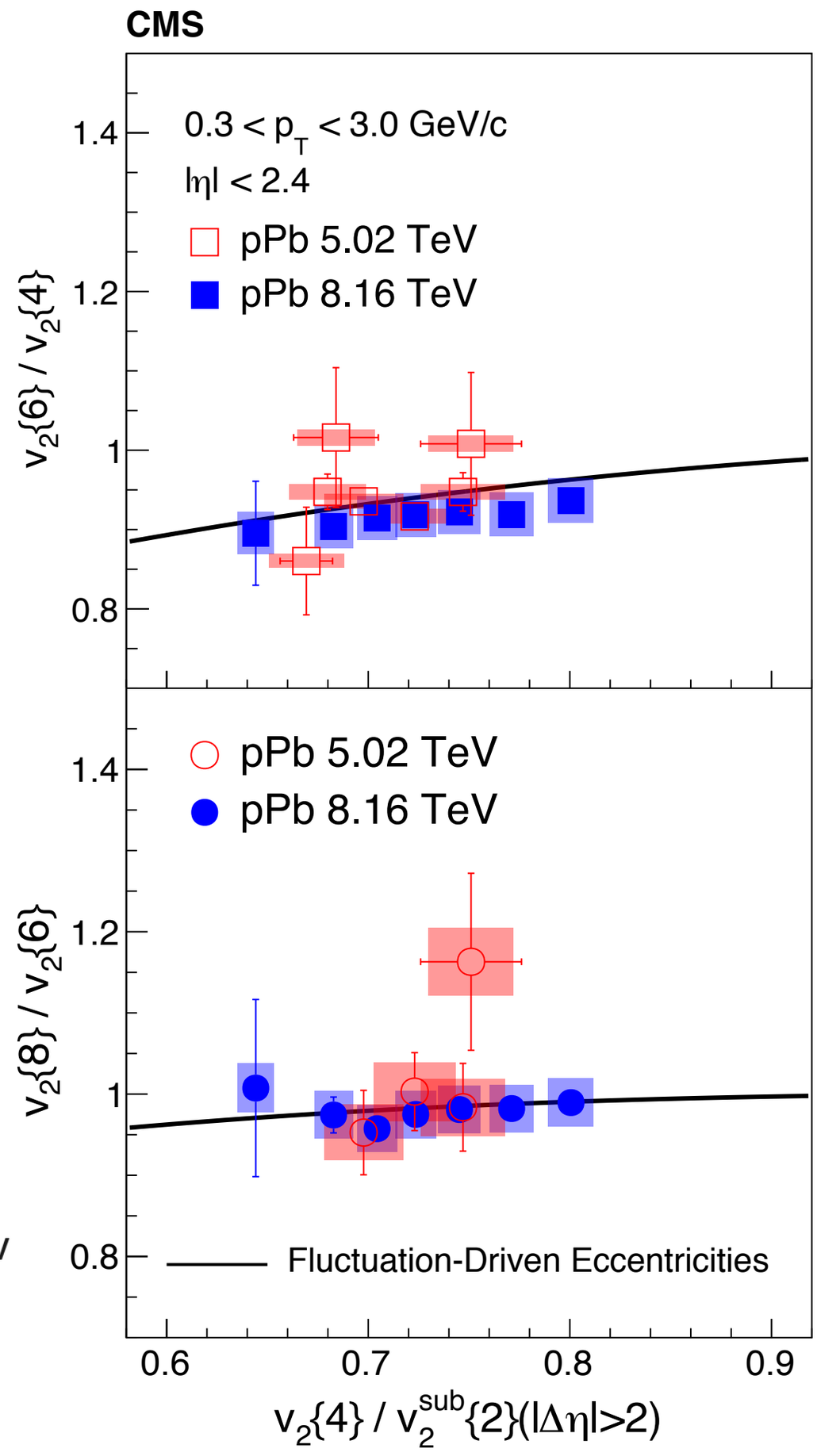
Quantitative agreement with experiment is excellent

I consider this the most solid proof of flow in p+Pb collisions, inspired by Art.

Multiparticle correlation studies in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV

CMS Collaboration • Albert M Sirunyan (Yerevan Phys. Inst.) et al. (Apr 25, 2019)

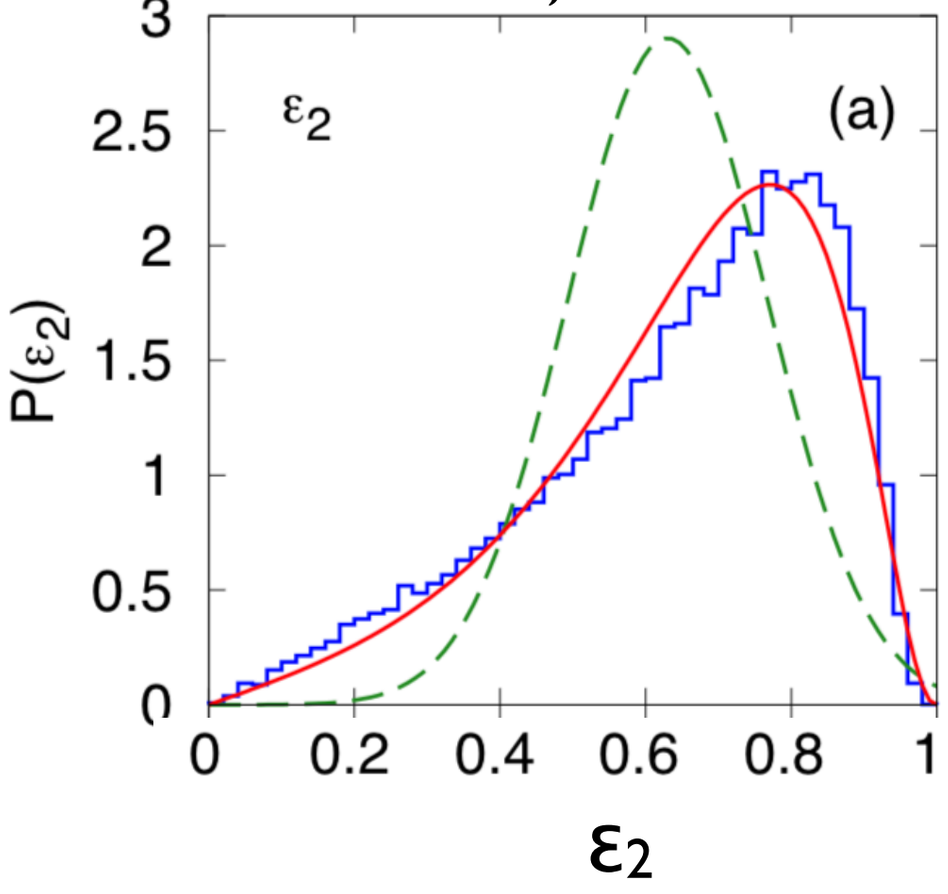
Published in: *Phys.Rev.C* 101 (2020) 1, 014912 • e-Print: 1904.11519 [hep-ex]



Art's problem solved

In 2014, I contacted Art and told him I had a possible solution to the problem he had pointed out in 2009, in case he was interested to test it. He was enthusiastic and started doing the fits immediately, and we wrote another 2 papers together with Li Yan.

Pb+Pb collisions, 75-80% cent.



Lucille and Art invited me (and my friends) Chez Panisse to celebrate as I was on a private visit in 2014.

U+U collisions

In 2016 and 2017, I visited Berkeley several times.
Art drew my attention to the recent analysis of U+U collisions by STAR. I told Giuliano Giacalone, then a MSc student, to look at these data. He was very excited. It inspired his PhD thesis.

Elliptic flow fluctuations in central collisions of spherical and deformed nuclei

Giuliano Giacalone (IPhT, Saclay) (Nov 9, 2018)

Published in: *Phys.Rev.C* 99 (2019) 2, 024910 • e-Print: 1811.03959 [nucl-th]

A matter of shape: seeing the deformation of atomic nuclei at high-energy colliders

Giuliano Giacalone (U. Paris-Saclay) (2020)

e-Print: 2101.00168 [nucl-th]

Giuliano was awarded the PhD prize of the Nuclear Physics Division of the European Physical Society in 2022.

At the same time, Art was still reading my most recent papers and giving me feedback, all the way through my last visit:

Jean-Yves:

Very interesting paper. But a basic assumption is the Gaussian distribution which you say is “solidly rooted in the central limit theorem." At the end you say it is not valid for p+A collisions. Early on you mention the upper cut-off in participant multiplicity due to the finite number of protons, but you say ”there is no deep theoretical reason that this is realistic” for the number of charged particles. As I said, for the lower beam energies, I think you are on weak ground.

I will come in Friday morning to talk with you. I can show you how to change the font of the references to make them look better.

Art

> On Jul 31, 2017, at 2:08 PM, Jean-Yves Ollitrault <jean-yves.ollitrault@ipht.fr> wrote:
>
> the paper on centrality and impact parameter will be posted soon. I am attaching a draft if you are interested.

Thank you